OBSERVATION OF MODE COMPETITION IN AN 11.4-GHZ MAGNICON AMPLIFIER

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Abstract

This paper describes the observation of pulse shortening in an 11.4-GHz magnicon amplifier due to competition with a parasitic gyrotron mode. The parasitic mode occurred only at high operating powers, when the beam transverse momentum was high, and its excitation caused the power in the output pulse to fall off substantially. We analyze the competition between the gyrotron and magnicon modes using a time-dependent multimode gyrotron simulation code that has been specially modified to model synchronous magnicon as well as nonsynchronous gyrotron interactions.

I. INTRODUCTION

A magnicon amplifier [1] is a scanning-beam device that makes use of a series of deflection cavities employing synchronously rotating TM_{110} modes to spin up a linear electron beam to high transverse momentum, followed by an output cavity containing another synchronously rotating mode to extract the transverse momentum in a gyroresonant fast-wave interaction to produce high power electromagnetic radiation. The output cavity can operate in a TM_{m10}, where m is a low integer, to produce radiation in the mth harmonic of the drive frequency. The output cavity interaction is analogous to that in a "small-orbit" gyrotron amplifier, and typically operates in the first cyclotron harmonic. However, because of the method of beam formation, the instantaneous guiding center of the electrons at the entrance plane of the output cavity precesses synchronously with the rotation of the magnicon mode, so that the interaction is invariant in a frame co-rotating at the rf drive frequency. This additional synchronism makes possible very high interaction efficiencies, and ensures the rapid startup of the magnicon mode, which normally suppresses all competing modes. However, the transverse beam momentum can also couple to nonsynchronous gyrotron modes by means of the cyclotron maser instability, and in some cases, such modes may compete with the magnicon mode [2].

This paper describes the observation of a parasitic 8.05-GHz gyrotron mode in the output cavity of an 11.4-GHz

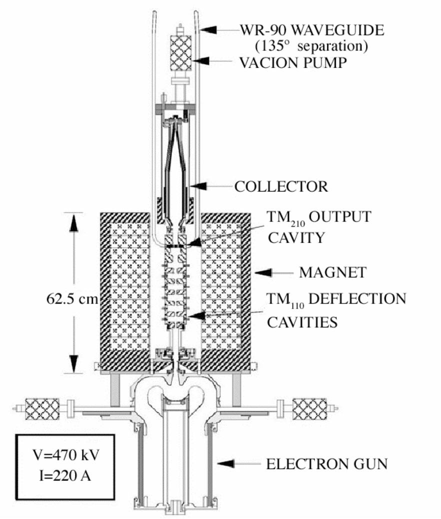

Figure 1. Schematic diagram of the 11.4-GHz magnicon amplifier, with old collector in place.

frequency-doubling magnicon amplifier experiment [1] (see Fig. 1). The parasitic mode was first observed following the installation of a new electron beam collector (see Fig. 2). It occurred only at operating powers above ~5 MW, when the beam transverse momentum was high, and limited the output pulse length at powers above this level. That is, tens or hundreds of nanoseconds after the start of the magnicon pulse, the gyrotron mode would grow to high enough power to interfere with the magnicon mode.

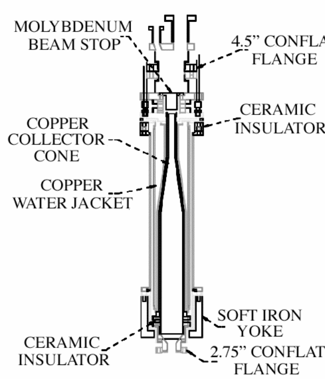

Figure 2. Schematic diagram of the new collector.

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14. ABSTRACT
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This caused the amplitude of the magnicon mode to drop off to a much lower level. We will compare the behavior of the magnicon and gyrotron modes to the predictions of time-dependent multimode simulations.

II. THEORY

In order to understand the problem of mode competition from nonsynchronous gyrotron modes in a magnicon device, it is useful to discuss the physics of these devices. Both the magnicon and the gyrotron are gyrodevices, in which the interaction with a resonant mode of the output cavity extracts principally the transverse momentum of the electron beam in a gyroresonant interaction that takes place near the cyclotron frequency or one of its *n* harmonics. The resonance condition is $\omega \approx \omega_{cav} \approx n\Omega_c + k_z v_z$, where ω is the angular frequency of the radiation, ω_{cav} is the resonant frequency of a cavity mode, Ω_c is the relativistic cyclotron frequency, k_z is the axial wave number of the cavity mode, and v_z is the axial velocity of the electron beam. In gyrodevices, an important parameter is the electron momentum pitch ratio α, which is the ratio of transverse to axial momentum. The higher its value, the stronger the coupling is to the rf mode, and the greater the potential interaction efficiency.

In most gyrotrons, the beam α is produced by adiabatic magnetic compression of some initial transverse momentum produced in the electron gun, and each electron gyrates at the cyclotron frequency about its own local guiding center. (In large orbit gyrotrons, the beam is produced differently, and each electron gyrates about a common guiding center along the axis of the device.) Phase bunching of the electrons in a gyrotron oscillator occurs due to a negative mass instability that bunches the electrons in the decelerating phase of the rf fields and produces radiation growth by extracting the transverse beam momentum. The threshold condition for oscillation is a function of the beam α, the cavity Q and length, and the coupling of the beam to the cavity mode.

In the NRL magnicon, the beam α is produced in a special way. A linear electron beam from an unmagnetized Pierce-type electron gun is progressively spun up in a series of six deflection cavities in a strong magnetic field using synchronously rotating TM_{110} modes at a drive frequency of ~5.712 GHz. The first cavity is driven externally, and the remaining cavities excited by the electron beam. This process produces a beam that gyrates near the cavity axis, and whose instantaneous guiding center precesses about the cavity axis at the drive frequency ω. The beam then interacts with the TM_{210} mode of the output cavity at twice the drive frequency in the first harmonic of the cyclotron frequency. This mode has *m*=2, and therefore rotates at ½ of its rf frequency, so that it is synchronous with the beam. The combination of frequency and phase synchronism results in an interaction with a very low threshold that starts up quickly, and that can be excited at very low values of beam α. However, as the output power is increased, the beam α at the entrance to the output cavity also increases, increasing the coupling to competing gyrotron modes.

III. EXPERIMENTAL OBSERVATIONS

Following the installation of a new electron beam collector, it was observed that as the output power of the magnicon was increased beyond ~5 MW, the power would fall off sharply within the pulse before the end of the drive pulse or voltage waveform, and that as the output power was further increased, the flat portion of the pulse continued to shorten. A microwave spectrum analyzer was used to assist in diagnosing the output. Fig. 3 shows a set of output waveforms from the magnicon. The main output pulse at 11.4 GHz drops off midway in the pulse, and at the same time an 8-GHz signal arises (top trace), as detected using a shorted slotted line tuned to the standing-wave minimum of the 11.4-GHz signal. One stage of the modulator PFN has been disconnected to produce a rounded voltage pulse. As the modulator voltage pulse rolls off, the 8-GHz signal vanishes and the 11.4-GHz signal begins to recover. Fig. 4 shows a spectrum analyzer measurement of the top trace, demonstrating that most of the spectral content is near 8 GHz rather than 11.4 GHz. Figs. 3 and 4 provided clear evidence of pulse shortening due to mode competition. We suspected that the competition was from a parasitic gyrotron mode. The 8-GHz signal was always present when pulse shortening was observed. In addition, a corresponding 8-GHz signal could be detected escaping from the collector, which is separated from the output cavity by a beam tunnel that is cut off at that frequency.

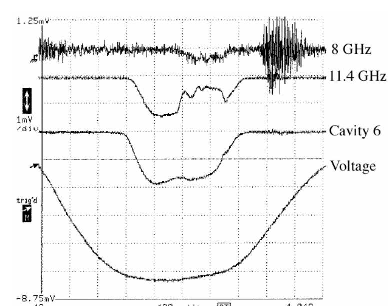

Figure 3. Oscilloscope traces showing 1) 8-GHz signal from a slotted line measurement of the pulse from one output waveguide, 2) 11.4-GHz signal from the second output waveguide, 3) rf signal from the last deflection cavity, and 4) modulator voltage waveform.

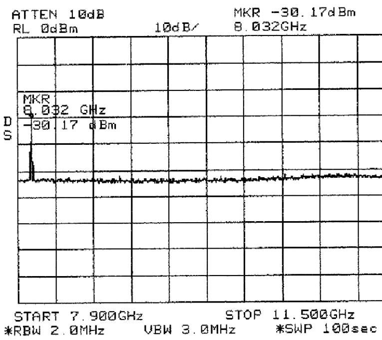

Figure 4. Spectrum analyzer measurement of the output signal from a shorted slotted line tuned to the minimum of 11.4 GHz standing wave.

IV. COMPUTER MODELING

A search was made for output cavity modes in the vicinity of 8 GHz using two computer codes, HFSS [3] and CLANS2 [4]. Fig. 5 shows the field pattern for a TE_{113}-like hybrid mode that was found by HFSS at 7.95 GHz. This mode has strong fields near the axis, and could be excited by a nonsynchronous backward-wave gyrotron mechanism, based on the transverse beam momentum that is induced as the beam is spun up in the deflection cavities to couple to the synchronous magnicon mode. A time-dependent multimode code [2] was used to model the competition between the magnicon and gyrotron modes as a function of beam α and the phase spread. An analytic fit to the calculated axial profile function for the hybrid mode was used in the model, which assumed that the hybrid mode had TE_{11}-like transverse fields. With reasonable assumptions, it looks like the parasitic gyrotron mode can start up in the presence of the magnicon mode, and grow to high enough amplitude to cause a falloff in the magnicon power, causing the observed output pulse shortening.

Fig. 6 shows a time-dependent multimode simulation of the output cavity interactions for a 200 A, 450 keV electron beam with α=0.7 for B=0.65 T. The magnicon mode is assumed to have a Q of 200, and the gyrotron mode is assumed to have a higher Q of 2000, due to ~90% reflection from the output window assembly. (This value comes from cold tests.) The partial trapping of the gyrotron mode increases its ability to compete with the magnicon mode. A critical parameter in the simulation is the phase spread, which models the degree to which the ideal magnicon phase synchronism between the beam and the rf mode (phase spread of 0) is degraded during the process of spinning up the electron beam. For a non-synchronous gyrotron interaction, the phase spread would be 1. In Fig. 6, a phase spread of 0.4 is assumed, corresponding to 72º of spread. It is noteworthy that the gyrotron mode can grow in the presence of the high-power magnicon mode, reaching its maximum power after a delay of ~50 ns. It is also noteworthy that the very inefficient gyrotron mode, which reaches less than 1% of the power of the single mode magnicon state, can cause the dramatic loss in magnicon efficiency, and that competition can exist between two modes widely separated in frequency.

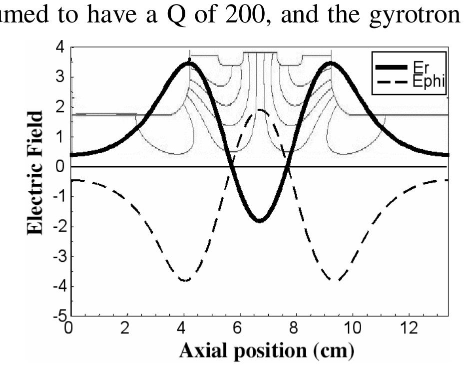

Figure 5 Field pattern of the TE_{113}-like hybrid mode of the magnicon output cavity, from calculations done by V.P. Yakovlev using the code CLANS2.

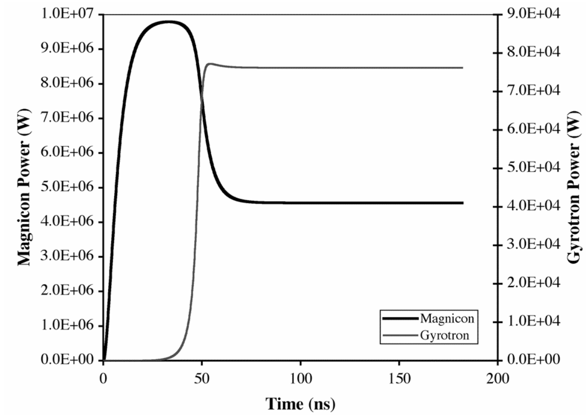

Figure 6. Time-dependent multimode simulation of competition between magnicon and gyrotron modes of output cavity.

Many simulation runs were carried out as a function of beam α and beam phase spread. Fig. 7 shows a summary of simulation results for the magnicon and gyrotron powers as a function of α. A phase spread of 0.4 is assumed. The magnicon single mode power is the value before the gyrotron mode grows large enough to cause the magnicon power to fall off. The magnicon multimode power corresponds to the steady-state value when the gyrotron has reached its maximum power. Note that there is a threshold in α for this process. Below α~0.61, the gyrotron mode is suppressed. At higher values, the gyrotron mode grows in the presence of the magnicon mode until a multimode equilibrium is reached. Also, the growth rate of the gyrotron is higher, and thus the length of the single-mode magnicon state is shortened, as the α is increased. Generally speaking, this is consistent with the experimental observations.

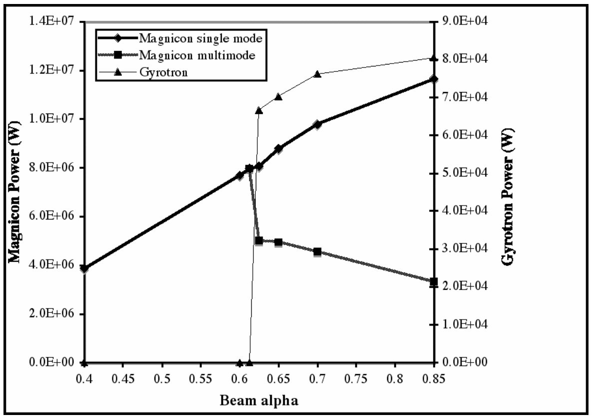

Figure 7. Plot of single mode magnicon output power, multimode magnicon output power, and gyrotron power as a function of beam alpha, from multimode simulation.

V. CONCLUSION

As a result of these measurements and simulations, the decision was made to remove the new collector. We reinstalled the old collector on 26 July 2006, and began to recondition the magnicon once more, as is needed after every vacuum break. The magnicon quickly returned to its previous level of performance with the old collector [1]. Pulse shortening phenomena still occur in high power operation, but 1-μs pulses can now be produced at output powers of up to 10 MW, which is more than twice what could be achieved when the new collector was still installed. In addition, the reason for the pulse shortening is different, since the 8.05-GHz mode is no longer present when pulse shortening is observed. This fact demonstrates that the new collector had been responsible both for the excitation of the parasitic mode, and for the resulting decrease in the magnicon output power. Following removal, the new collector was cold tested and a resonance found at 8.07 GHz, near the frequency of the parasitic mode. While the exact mechanism is not clear, it seems likely that this resonance affected the growth of the output cavity parasitic mode.

VI. ACKNOWLEDGMENTS

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